

An Electronic Digital Computer

By

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Reprinted from



August and September, 1951

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Using Cold Cathode Counting Tubes for Storage

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A small sequence-controlled computer is described; it has storage capacity for up to 90 numbers each of eight decimal digits. Cold cathode counting tubes (Dekatrons) are used as storage elements. Parallel operation is employed, and the speed of operation is comparable with that of a desk calculating machine. Apart from speed, however, the computer provides most of the facilities found in larger, faster digital computers. Information is fed into the machine from perforated paper tapes and a teleprinter or tape perforator records the results.

SEVERAL large-scale computers have been described in recent years, including the ENIAC^{1,2} with hard valve circuits, the EDSAC^{3,4} with mercury delay storage, the University of Manchester computer^{5,6} with cathode-ray storage and the Birkbeck College computer with magnetic storage.^{7,8} These computers are intended primarily to carry out enormous computations, too lengthy to perform by other means. In addition smaller scale relay computers^{9,10} have been built for general work. The machine described here is not intended to deal with the long calculations for which the large computers have been designed. It is intended rather to do the work of a few operators with

place. In the present machine these two parts are almost entirely separate.

Because a relatively low operating speed is accepted, it becomes practical to read orders and other data from the perforated tape as they are needed in the calculations (this is done in the B.T.L. machine^{11,12}). Design is thus simplified and much less storage capacity is needed. The low operating speed also makes possible the use of relays for routing and sequence control. Since each relay may carry many contacts this leads to simplicity in setting up connexions. The fact that the techniques are well established and of proved reliability is of great importance.

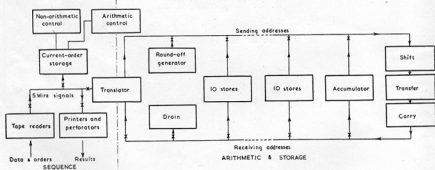


Fig. 1. Block schematic diagram of computer.

desk calculating machines where the work to be done is of a routine or repetitive nature. As a result, simplicity and reliability have been regarded as of more importance than speed of operation and the machine performs the operations of addition, subtraction, multiplication and division little faster than a desk calculator.

Fig. 1 is a schematic diagram of this machine. The design can, for convenience, be regarded as consisting of two parts. The first includes the means by which the machine receives orders, controls the sequence of operations and the routing of numbers to and from the stores, and prints the results. The second part consists of the means of storing numbers and, closely allied with this, the arithmetic unit in which the arithmetical processes take

Numerical data obtained in the course of the calculation must be stored in the machine. The use of relays for number storage is not attractive, as many relays would be needed. Other methods were considered, largely for their suitability for use in a computer with relay routing, and it was eventually decided to make use of cold cathode counting tubes ("Dekatrons") (Ericsson Type GC10A). These were recently described¹³ and are coming into increasing use for scaling and counting purposes. In these tubes, a gas discharge may be stepped round in to any of ten stable positions, and each tube is therefore capable of storing a decimal digit. The tubes have the advantage that numbers can be fed into them, or obtained from them, by use of relatively simple circuits. Moreover the numerical information is in the form of large amplitude pulses (tens of volts), so the possibility of spurious pulses being introduced from external

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sources is much reduced by comparison with other storage methods. Use of these tubes permits the computer to work on a decimal, rather than a binary, basis. This is convenient from several points of view; it is particularly advantageous in a parallel computer, since the number of digits and therefore the number of parallel arithmetical units, is considerably reduced.

Provided that the number of stores required is not too large, this method of storage is thought to compare favourably with other methods on the basis of cost, size, and power consumption per digit. When the computer is fitted with its full storage capacity (90 eight-digit numbers, equivalent to 2,700 binary digits) just over 800 tubes will be used. The power consumption is about 150W per tube at 370V. From the fact that the tubes operate at this low current and from life tests to date, tube life is expected to be many thousands of hours.

Each storage address consists of nine tubes, corresponding to eight digits with one additional tube to indicate the sign. The decimal point is regarded as being after the first figure of the number stored, whether this is a significant figure or zero, and the capacity n of each store is $+10 > n > -10$.

Numbers are fed into stores and handled in the arithmetic unit as trains of pulses. Negative numbers are handled as complements except on the punched tape and when finally printed, when they appear as modulus and sign. The basic process of addition (or subtraction by addition of the complements) is carried out electronically in order to save the wear that would occur if high speed relays were used. Multiplication and division is by a sequence of multiple additions (or subtractions), with the operation of a relay circuit to shift the decimal point as each multiple addition takes place.

No provision is made for reading off tables of functions and the low operating speeds will often make it impracticable to calculate the required functions *ab initio*. This must be regarded as a limitation of the present machine; it may eventually be overcome by providing a special table-reading attachment.

The computer has been operating with 20 eight-digit stores for some months. This has made possible the establishment of most of the electronic and relay circuits. Although the machine has not yet been put into service it seems appropriate at this time to publish details of the design which has been established.

The computer contains about 380 relays, 18 Dekatrons, 80 thermionic valves and 40 cold cathode triodes, plus 28 relays and 90 Dekatrons per ten stores. It occupies three 7 ft. Post Office racks, together with an additional rack per four groups of ten stores, one smaller rack for the power supplies and a table for tape readers and printers. Total power consumption is about 1kW.

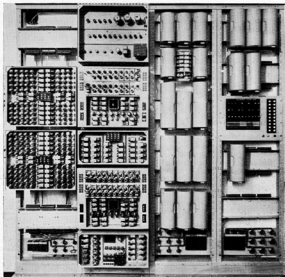
Facilities

The computer operates solely under the control of orders and data fed in from perforated paper tapes, and no manual switching or plugging in is necessary. Provision is made for a maximum of eight input tapes read by separate tape readers. Each tape may contain orders, input data, and

constants. A typical allocation of tapes is expected to be a master programme tape, a tape giving the data relevant to the particular problem and a number of closed loops containing the longer sub-routines.

The output of the computer is fed into either a perforator or a modified teleprinter operating as a page printer. A maximum of eight printers and perforators can be accommodated although only a few of the positions are used at present. It is possible to feed the perforated tape from an output perforator into an input tape reader to give a long-term storage when the nature of the work permits.

The first order is always read from tape reader No. 01 and subsequent orders come from the same source until an order specifies a change. If the source of orders is changed to a Dekatron number store, orders are drawn from successive stores until the sequence is interrupted. Orders are normally only stored in the Dekatron stores when they take the form of short sub-routines or if they are to be



Computer fitted with 20 stores, but excluding tape readers, printers and power supply. The left hand rack carries two units each of ten stores. The left centre rack carries the electronic pulse generator (top), the arithmetic units with relay shift unit (centre) and the translator unit (bottom). The two right hand racks contain the relay sequence control circuits.

subjected to arithmetical operations; the majority of orders will be read directly from the tape readers.

Orders appear on the tape as blocks of five (decimal) digits and each digit is represented by one row of perforations. Numerical data are perforated as blocks of eight digits preceded by a sign character. Blocks of digits are separated by a character which can be either a space or one of ten block-marking characters. A search facility is provided by which any tape reader can be made to search along its tape until it finds the required block-marking character.

ARITHMETICAL ORDERS

Arithmetical orders consist of one digit defining the

arithmetical operation to be performed, a sending address (two digits) and a receiving address (two digits). The sending address may be a Dekatron store, the accumulator, a tape reader, or the rounding-off circuit. The receiving address may be a store, the accumulator, a printer or perforator, or a drain for unwanted numbers. Seven operation digits have been allocated as follows:

- (1) Add the contents of the sending address into the receiving address, and leave the contents of the sending address unchanged.
- (2) Add the contents of the sending address into the receiving address and clear the sending address.
- (3) Subtract and do not clear the sending address.
- (4) Subtract and clear the sending address.
- (5) Multiply the contents of the sending address by the contents of the "receiving address" clearing the latter, and add the product into the accumulator.
- (6) Divide the contents of the accumulator by the contents of the sending address, form the quotient in the receiving address and leave the remainder in the accumulator.
- (7) Add the positive modulus of the contents of the sending address into the receiving address.

The sending and receiving addresses must not lie in the same group of ten stores; in the case of multiplication and division they must not refer to an input or output organ. It should be noticed that addition and subtraction do not require the use of an accumulator, because the result of a direct transfer of the contents of a store into an already occupied store is to form a sum. In this operation the original number in the latter store is lost unless it is also stored elsewhere. The accumulator is only required as a third address, of length 15 digits, for the purpose of multiplication and division, but it can be used exactly as a normal store at other times.

NON-ARITHMETICAL ORDERS

In non-arithmetical orders the operation digit is "0" and is followed by two further digits calling for a change of the address from which orders are obtained, search for a block-marking character, examination of the sign of the number in a specified address, or selection of the layout of the printed result. The last two digits specify the address concerned.

The sign examination facility allows the future action of the computer to be controlled by the state reached by the calculation. Any store can be examined for the presence of either a positive or a negative sign. If the sign looked for is found, an affirmative relay is locked in and any subsequent conditional orders (see below) are performed; otherwise they are ignored.

The order calling for a change in the order source can be made conditional or unconditional; if conditional it is only performed if the previous sign examination has given an affirmative result. This allows a new set of orders to be brought in when the previous set has brought the calculations to a desired stage.

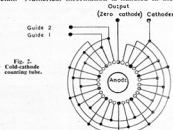
The order requiring a search for a block-marking character causes all the information to be ignored which lies between the present position on the tape and the specified character. This can again be made conditional on the result of the previous sign examination. Facilities are provided for the tape to be searched in either the forward or the reverse direction, although the tape readers at present available only allow search in the forward direction. The ability to search in reverse will allow sections of the order tape to be used repetitively without necessitating a closed loop of tape.

The print layout is variable to a limited extent. There are ten layouts available for printing each eight digit number, for instance one such layout might consist of the eight digits followed by spaces, and another the eight digits followed by line-feed and carriage return. An order is required to define which layout is to be used, and it stays in force until replaced by another print layout order.

Arithmetical Operations

ADDITION AND SUBTRACTION WITH SINGLE TUBES

As has already been stated, addition is the fundamental operation. Subtraction is effected by adding the complement, and multiplication (or division) by a sequence of multiple additions (or subtractions). The circuits used for adding a number from one store into another therefore form the basis of the arithmetic unit, and are described in detail. Numerical information is handled in the form of



trains of up to nine pulses. Each train represents one decimal digit, and as parallel operation is employed there is a separate channel to handle each digit. For normal arithmetical operations the pulses are routed, through a transfer unit, from one store to another, or to the "accumulator." When a digit is being fed from a store to a printer, a "translator" unit is used to convert the train of pulses into a form suitable for operating the relays which control the printer. The same translator is used when reading numerical information into the computer to convert digits stored on relays into trains of pulses. It is connected to the transfer units in exactly the same way as a store, but only handles one digit at a time.

It is first necessary to consider the mode of operation of the gas-filled tubes (Dekatrons) which form the basis

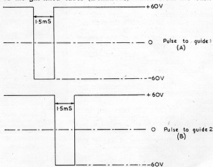


Fig. 3. Pulse to operate counting tube.

of the storage system. The arrangement of a Dekatron is shown diagrammatically in Fig. 2. Ten cathodes are equally disposed round a central anode, and all but one are connected together. Between adjacent cathodes there are two guide electrodes, and these are connected together in the way shown.

Normally the zero cathode is taken through a resistor to earth or to a small bias potential, and the remaining cathodes are earthed. The guides rest at +60V and the anode is connected through a resistance of 1M Ω to +370V.

Pulses of the form shown in Fig. 3 are applied to the guide electrodes to move the discharge from one cathode to the next. During the first pulse the discharge moves to the next guide 1 electrode. At the end of the first pulse the discharge moves on to guide 2, which is then more negative than the previous cathode. At the end of the second pulse, the discharge moves to the nearest cathode, and has advanced one step. It is not necessary for the two guide pulses to overlap, but it is important that any time interval between the end of the first pulse and the start of the second should not be comparable with the de-ionization

right anode the complement on 10. These pulses are suitable for direct connexion to one guide of the receiving tube. Since, for the purpose of subtraction, the complement on 9 is required, it is arranged that only 9 pulses are applied to the other guide on the receiving tube (Fig. 5(g)) so that the first pulse of the train shown in Fig. 5(e) is ineffective in moving the discharge.

If the sending tube is to be cleared to zero during the transfer, the complement output of the transfer unit is connected to one of the sending tube guides in place of the train of ten pulses. This method of clearing stores is also

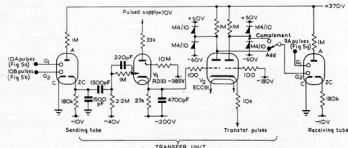


Fig. 4. Transfer circuit

time of the Dekatron tube. A small overlap has been provided as a precaution against possible failures. If pulses are applied to one guide only, the discharge returns to the same cathode after each pulse.

The method used to pass a digit into the tube is to apply n pairs of pulses of the type shown in Fig. 3 to the guide electrodes. The discharge will then advance by n steps, and if the discharge starts from zero, or output, cathode, it will move to cathode n .

To read a digit out of a storage tube, a train of ten pairs of pulses may be applied to the tube, causing the discharge to circulate and return to its starting point. A pulse is produced as the discharge passes the zero or output cathode, and the number of pulses of the train of 10 which occur after the output pulse is an indication of the digit stored on the tube. Further, the number of pulses preceding the output cathode pulse is the complement on 10 of the digit stored in the tube.

The function of the transfer unit is to accept the output cathode pulse from the Dekatron tube from which the digit is being taken ("sending tube"), and from it to derive the pulses representing the digit and complement, either of which is passed to the receiving tube. Fig. 4 is a circuit of one transfer unit, and Fig. 5 shows the waveforms appearing when the digit 3 is transferred. When an addition is to be performed, a relay is energized in a pulse generator unit, which, after a short delay to allow any transients from the relay circuits to die away, produces a train of ten pulses as shown in Fig. 5(a) and 5(b). These pulses are applied to the sending tube, which therefore steps round by one complete revolution. When the discharge arrives at the output cathode, a waveform of the form shown in Fig. 5(c) is produced, and this is used to trigger the cold cathode triode V_2 . The cathode potential of V_2 rises from -200 to -160 , and the left half of V_2 conducts.

Pulses are applied to the cathode of V_2 synchronously with those shown in Fig. 5(b), but at a different D.C. level, and, prior to V_2 being triggered, they produce negative pulses at the right anode of V_2 (Fig. 5(e)). When V_2 is triggered the pulses appear at the left anode (Fig. 5(f)). It will be seen that the left anode delivers the digit, and the

right anode the complement on 10. These pulses are suitable for direct connexion to one guide of the receiving tube. Since, for the purpose of subtraction, the complement on 9 is required, it is arranged that only 9 pulses are applied to the other guide on the receiving tube (Fig. 5(g)) so that the first pulse of the train shown in Fig. 5(e) is ineffective in moving the discharge.

To extinguish V_1 and minimize the chance of spurious triggering taking place, H.T. is removed from its anode from the end of each operation until the start of the next.

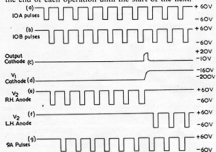


Fig. 5. Transfer circuit waveforms.

MULTI-DIGIT ADDITION AND SUBTRACTION

As well as the transfer circuits described above, circuits are needed to perform carry over, when required, from each digit into the next most significant. The "carry" circuits consist of a cold cathode valve which is triggered when the receiving store reaches or passes zero. This valve remains conducting until the end of the train of transfer pulses, when a second valve performs the carry over and the first is extinguished. A transfer and a carry circuit is required for each digit. Fig. 6 is a diagram showing the connexions for a four-digit store with carry circuits. It will be noted that the most significant tube has a carry

circuit, and carry over is made into the least significant tube.

This carry circuit plays no part in handling positive numbers, but is necessary to handle complements. When the complement of a multi-digit number is found, the complement on 10 is required for the least significant digit and the complement on 9 for all the other digits. It has already been explained that in this machine the complement on 9 is found for all digits; there is no simple means of checking electrically which tube in a store carries the least significant figure. Carry over from the most significant tube to the least significant corrects this, as can readily be demonstrated, and enables the complement on 9 to be used in every case, whether in finding the complement of a

all carry units indicates that the carry operation is complete. This is arranged to stop the pulse generator and send a "finish" signal to the relay sequence control circuits, which then proceed with the next step.

Means must be provided on each store to show whether the content is a positive number, or a complement (representing a negative number). This could be done by some device (for example a cold cathode trigger valve) having two stable states, but for circuit convenience an additional Dekatron has been used in each store. An additional transfer and carry unit is used, wired so that the sign tube receives the carry over from the most significant tube. Carry over from the sign tube is passed into the least significant tube.

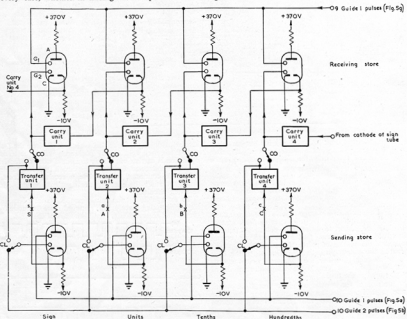


Fig. 6. Arrangement of transfer and carry units for three digit operation.

number or finding the number from its complement.

The arrangement of the carry circuit is shown in Fig. 7. The pulse generator continues to produce the pulses shown in Fig. 5(g) (applied to receiving tubes) after the main train of V_1 is completed. It also provides pulses for application to V_2 cathode similar to those applied to the cathodes of the V_1 tubes in the transfer unit but on a separate wire and not beginning immediately after the train of transfer pulses. When V_1 reaches or passes zero, V_2 is triggered, and the potential of the left grid of V_2 is raised. When a pulse is applied to V_2 cathode it then appears at the left anode and is applied to the grid of the next most significant receiving tube. A pulse is applied simultaneously to the anode of V_2 and V_1 extinguishes the discharge. Subsequent pulses applied to V_2 cathode appear at the right anode of V_2 . The simultaneous appearance of pulses at the right-hand anodes of the

For positive numbers the sign tube is at zero, and for complements at 9. A double triode is connected to the output cathode of the sign tube, and this operates two relays corresponding to + and -. The contacts of these relays give sign information required when multiplying, dividing or printing. It is also arranged that a warning is given when this sign inspection circuit is not connected to any tube, perhaps as a result of faulty address selection.

MULTIPLICATION AND DIVISION

Division necessitates the use of a special store (the accumulator) having 15 digits, since when an 8-digit quotient is to be obtained with an 8-digit divisor, there are cases where difficulties would arise if a 15-digit dividend were not provided. An accumulator of more than eight digits also reduces errors in rounding off the product of multiplication if products are repeatedly summed in the accumulator. A further advantage of a long accumulator

information obtained via a relay circuit from a punched paper tape into a form suitable for operating the transfer units in the computer and vice versa. The translator is brought into circuit in the same way as any storage address and no alteration is needed to the transfer unit to accommodate it.

The basis of the unit is a special Dekatron in which the cathodes are all brought out separately. For this purpose a 10-cathode tube would be suitable, but the tube available has 11 cathodes (GS11A) and this has been used.*

The method of operation is shown in Fig. 8. If, for example, the numeral 3 is to be fed into the computer, one of the Dekatron cathodes, No. 7 in this case, is connected to the input of the transfer circuit by relays energized from the tape reader. When translation-in takes place, the discharge in the GS11A is stepped round by a train of 10 pulses to cathode No. 10. In passing the selected cathode, a pulse is fed to the input of the appropriate transfer unit. The transfer unit then functions in the normal way and if a positive number is being translated, the remaining pulses

on which the discharge is left rises in potential from $-16V$ to something positive with respect to earth, causes the grid potential of two of the triodes V_{II} to V_{IS} to rise, and so closes two of the relays $PA/1$, $PB/1 \dots PE/1$. The contacts of these relays operate the teletypewriter or tape perforator. The metal rectifiers in the cathode circuits of the GS11A give an output in the appropriate code (i.e., the 10 combinations of 2 holes punched in two of five spaces) for this purpose.

After translation-in or -out a separate circuit returns the discharge in the GS11A to cathode No. 0 before the translator is again required for use.

Sequence Control

This part of the computer controls the tape readers and output organs, selects the Dekatron stores required for each arithmetical order and interprets these orders as a sequence of the basic functions of addition and subtraction. It is designed to operate as an asynchronous system in which each switching operation in the sequence is

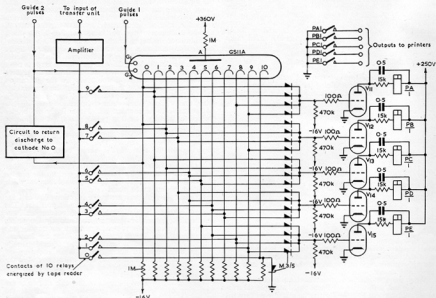


Fig. 8. Translator unit

of the train of 10 (in the example, 3) are passed to the receiving store by the transfer unit. When translating in negative numbers the transfer unit is arranged to complement them. Since the translator deals with only one digit at a time the remaining transfer circuits are arranged to transfer zeros (or nines in the case of a complement). The translator is connected via the transfer circuits to each digit of the store in turn by the relay shift circuit.

When translating out (i.e., taking information from the computer) the GS11A tube again starts from cathode No. 0, but in this case it steps round by the number of pulses delivered to it by the transfer unit. The cathode

* Subsequently replaced by Ericsson Type GS12A with 12 cathodes, which supercedes GS11A.

checked before the next is allowed to begin. This simplifies maintenance by eliminating critical relay timing and by stopping the computer immediately a circuit fault is detected.

The sequence of an arithmetical operation can be regarded as consisting of three parts:—

- (1) Reading in the current order.
- (2) Setting up the necessary connexions.
- (3) The arithmetical operation itself.

Non-arithmetical orders are dealt with in a similar manner and the operation of the computer continues until a special order is reached which leads to the lighting of the "Finish" lamp and prevents any further operations.

READING IN THE CURRENT ORDER

Each order is transferred, digit by digit, from the perforated tape or Dekatron store into the relay order storage circuit and is then interpreted as a sequence of additions and subtractions. The address from which the order is obtained has been derived from an earlier order calling for a change of order source. This address is stored on a group of relays which mark out the two digits of the order source address. The "tens" digit energizes a relay connecting a group of ten addresses as the sending store and the "units" digit selects the individual store in this group. The reading-in sequence begins when it has been proved that the correct tens and units relays have operated. If the order source is a tape reader the sequence will consist of six cycles. The space or block-marking character is read during the first cycle and the order digits during the remaining five cycles. At the beginning of each cycle the appropriate relay storage group is connected to the five-wire output of the tape readers.

The contacts of each tape reader correspond with the pattern of holes on the tape, and they operate the equivalent combination of five relays in the storage group to which they have been connected. The relay storage group into which the space or block-marking character should be routed will only allow the next cycle to commence if it receives a particular combination of one hole out of five (the space combination) or any combination of three holes (the block-marking characters). The five storage groups into which the order digits are fed will only allow the next cycle to commence if each receives one of the ten combinations of two holes. If the tape reader moves the tape forward more than one row before reading the next character, or fails to move the tape, a digit storage group will be offered the space code or vice versa. Furthermore, any erratic operation of the reading contacts is unlikely to distort a two-hole code into another two-hole code, so that any faulty operation of the tape reader is almost certain to be detected.

SETTING UP THE CONNEXIONS

The source from which the current order has been read and the relay storage group are now disconnected, leaving the order stored on the relays. If this order requires an arithmetical operation the sending and receiving addresses are selected and connected to the input and output of the transfer system in the following way. The Dekatron stores are built in units each containing ten stores of eight digits and sign. These units are a convenient size and suit the decimal address code. Each group of ten stores has switching relays which connect it either to the input or the output of the transfer systems. These are the sending and receiving "tens" relays. When a "tens" relay is energized the Guide 2 electrodes of all the sign storage Dekatrons in the group are connected to the sign input or output lead of the transfer system, all the Guide 2 electrodes of the 1st digits to the 1st digit lead, and so on. The individual store in the group is selected by one of ten switching relays (the "units" relays) which connects Guide 1 pulses to all the Dekatrons of one address. Thus although all the 90 Dekatrons in the group of 10 addresses receive Guide 2 pulses, only those of the selected address receive pulses on both guides and the position of the discharge can change only in this one address.

The two sets of "tens" and "units" relays which bring the sending and receiving addresses into action are selected and checked by four groups of address storage relays. A fifth group stores the operation to be performed and, provided that the addresses selected are compatible with the operation demanded, sets up the arithmetic control relay circuits. As a further guard that the sending and receiving addresses are connected correctly the arithmetic sequence cannot start until the signs of both addresses and of the accumulator have been identified.

THE ARITHMETIC OPERATION

When the selection of function and addresses is complete the arithmetical sequence begins. It occupies a variable number of cycles, only one for addition or subtraction, nine for multiplication, ten for division, 11 for reading in a number from the tape and up to 19 for printing a number in a maximum length print layout. For addition or subtraction the single cycle has two steps: setting the shift circuit to the straight-through condition and carrying out a single transfer. For division of a positive dividend by a positive divisor each cycle has three steps: setting the shift to successive positions, carrying out a multiple subtraction until the sign of the accumulator changes, and carrying out a single addition. The completion of each step is checked before the next can begin.

When the arithmetic sequence has produced the full number of cycles required for the particular operation the address relays are released, the stored order is cleared down and the next order reading sequence begins.

PRINTING OUT

If the current order selects the printer as the receiving address the translator is connected to the output of the transfer system and the printer is connected to the five-wire output of the translator. A previous order will have specified the print layout which is to be adopted. Each cycle of the arithmetical sequence then consists of three steps. The first sets the shift to route each digit in turn to the input of the translator (which accepts only one digit at a time). At the same time the translator is recycled to zero. During the first step there may alternatively be connected to the printer the contacts of one of a number of relays which mark out non-digit characters such as space, line feed and carriage return. The second step is a single addition or subtraction. If a non-digit character has been selected by the first step this transfer is not required. The teleprinter with page printing attachment has been modified so that five-wire signals operate magnets controlling the five combs of the combination head. The third step of each cycle sets the combination head of the teleprinter by operating these magnets from the output of the translator or a character relay, checks the position of the combs, and prints a character.

Conclusion

It is believed that the computer described above will meet a real need in the computing field. It is particularly suited for cases in which the same calculation must be performed many times on a variety of numerical data. Its use is expected to be an economical proposition in many cases when the cost of a large, fast computer would not be justified.

Acknowledgment

The authors have received much helpful advice from Dr. J. Howlett, and during the early stages of the work they benefited by a discussion with Professor D. R. Hartree. The work was carried out as part of the programme of the Electronics Division at A.E.R.E. and is published by permission of the Director, A.E.R.E.

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